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Comparison of Two Control Programs of the VVER-1000 Nuclear Power Unit Using Regression Data Mining Models

A load-following mode of nuclear power plants (NPP) is a complicated procedure because there are significant changes in many interrelated processes. In order to show which control program (CP) of NPP is better to use, data mining (DM) techniques can be introduced. This study proposes a DM approach in order to show a possibility of using DM regression models for NPP. The datasets for DM were obtained by simulating two static CP of VVER-1000 NPP in Simulink software of Matlab program package.

Keywords: VVER-1000, data mining, regression models, nuclear power plant.

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Порівняння двох програм керування ядерним енергоблоком ВВЕР-1000 з використанням регресійних даних моделей інтелектуального аналізу даних

Режим навантаження атомних електростанцій є складною процедурою, оскільки в багатьох взаємопов'язаних процесах відбуваються суттєві зміни. Для того щоб показати, яку програму керування (ПК) АЕС краще використовувати, треба запровадити методи інтелектуального аналізу даних (DM). У цьому дослідженні запропоновано підхід інтелектуального аналізу даних для демонстрації можливості використання моделей регресії до АЕС. Набори даних для DM отримано імітацією двох статичних ПК АЕС ВВЕР-1000 у програмному забезпеченні Simulink програмного пакету Matlab.

Ключові слова: ВВЕР-1000, інтелектуальний аналізу даних, регресивні моделі, АЕС.

At the present time, a lot of countries have to use a load-following mode at NPP because other types of power plants have almost completely exhausted their adjustment possibilities. To solve such problems, all complex techniques and automatic control systems which allow switch of the existing NPP in a load-following mode were developed.

To show advantages and results of two CP based on intelligent systems, there is the need to use DM processes. As the Simulink and DM are the different ways of using some techniques, another view of processes related to energy systems will be shown. Moreover, using others techniques will allow hidden dependences between various characteristics to be discovered.

Background

Usually thermal, solar, wind and hydroelectric power plants are used to control the daily schedule load of grid, but today their adjustment possibilities are almost completely exhausted and there is the need in a massive daily stop of large power units or else, some unload of NPP in the near future [1]. This kind of problem contributes changes into a balance of power in the country's grid as a whole, and, therefore, it is frequently necessary to switch existing nuclear power plants in the load-following mode, which changes many processes associated with changes of in-house power. As a consequence, this leads to a loss of stability and reliability required for NPP, as well as additional economic expenses [2]. Changing the power of the reactor is substantially determined by its physical characteristics and especially by the effect of the periodic redistribution of power by volume of the core, the so-called xenon oscillations. Xenon transient processes affect the NPP maneuverability [3].

The advanced automatic control system that implements a compromise-combined CP showed better results than the CP of the power unit with the constant average temperature of the coolant in the primary circuit [4]. The results were obtained by Simulink of Matlab software package.

However, in some cases, it is not sufficient and it is necessary to implement a complex and comprehensive estimate of the transfer from one power point to another. This estimate is implemented on the basis of forecasting. It is very important to carry out an estimate as accurately as possible and if the forecast is more accurate, it will provide a higher financial result. On the one hand, not good planning and forecasting lead to higher economic expenses than expectations and, accordingly, to an inefficient redistribution of NPP power. On the other hand, it leads to the risk of possible errors as a result of a comprehensive estimate of power coverage [5].

Control programs. A load-following mode of the power unit occurs by static CP. These programs show the dependence of the technological parameters of the power unit in steady conditions. There are many different CP of the power unit, but the CP of the power unit with the constant average temperature of the coolant in the primary circuit, which is widely used in practice, and the previously developed advanced automatic control system that implements a compromise-combined CP have been selected as the object of research.

Using the Matlab software package, the above CP was recreated. It is presented in Fig. 3. More detailed information about them is described in the two related works [6, 7].

Multi-zone model of VVER-1000. In this paper, the mathematical multi-zone model of the VVER-1000 implemented in the Simulink software of the Matlab package was used. This model allows getting sets of data for further analysis using DM. Such mathematical model considers all features associated with

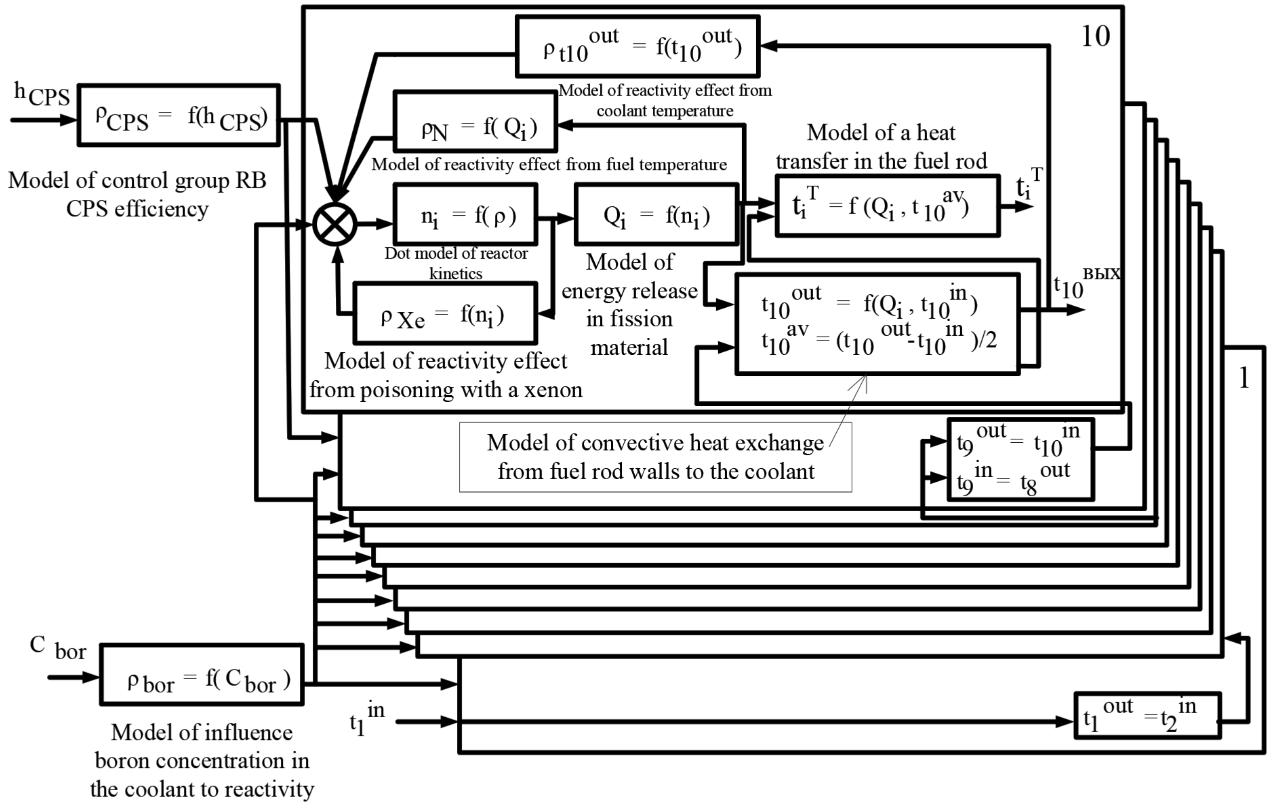

Fig. 1. The mathematical multi-zone model of VVER-1000

the dynamic processes which are described by the system of nonlinear differential equations. In order to solve and study some of the technical problems, the dot kinetic model is often used, but this solution is not suitable for the establishment of an adequate NPP model, because of the inability to control the main parameters of the reactor, such as changes in temperature of the coolant in the reactor core, the axial offset (AO), fuel temperature etc. Thus, the developed reactor model has the core divided into ten sections by height. Each zone of the model has the same structure. The only difference is in the geometric and thermo-hydraulic parameters of each zone and, accordingly, various static and dynamic properties. The mathematical multi-zone model of the VVER-1000 reactor is shown in Fig. 1. More detailed information about the multi-point mathematical model VVER-1000 is provided in [8].

Model simulation in Simulink. The model simulating of the VVER-1000 core unit cell includes 26 differential equations, 3 input parameters: (h_i;$C_{i,b}$;$t_{i,w,in}$) and 4 output parameters: (Φ_i;Q_i;$t_{i,w,out}$;$t_{i,f}$). As a result, using the Simulink suite of MATLAB, a distributed model of the VVER-1000 core allowing us to take into account the distributed processes in the core in power-follow mode was created (Fig. 2).

The improved method for automated control of the VVER-1000 power under variable loading conditions using 3 control loops and allowing us to improve the known programs for controlling the VVER-1000 power with a constant core average coolant temperature $\langle t \rangle$=const and a constant second circuit inlet steam pressure $\langle p_2 \rangle$=const is based on this distributed simulation model of the VVER-1000 core. The schematic diagram of these improved reactor power CP is shown in Fig. 3.

The following components are shown in Fig. 2: 1 is <t> (program 1) or $\langle p_2 \rangle$ (program 2) regulator; 2 is turbine control mechanism; 3 is safety-rod actuator; 4 is <t> selector; 5 is turbine rotating frequency selector; 6 is turbine rotating frequency regulator; 7 is servomotor; 8 is p2 selector; 9 is reactor; 10 is p2 primary detector; 11 are turbine regulating valves; 12 are reactor coolant temperature sensors; 13 is turbine; 14 is ion chamber; 15 is steam generator; 16 is turbine rotating frequency sensor; 17 is electric generator; 18 is reactor coolant pump; 19 are boric acid and desalted water regulating valves; 20 is boric acid and desalted water supply control mechanism; 21 is reactor unit power regulator; 22 is electric generator power selector; 23 is boost pump tank; 24, 25 is AO regulator and selector, respectively

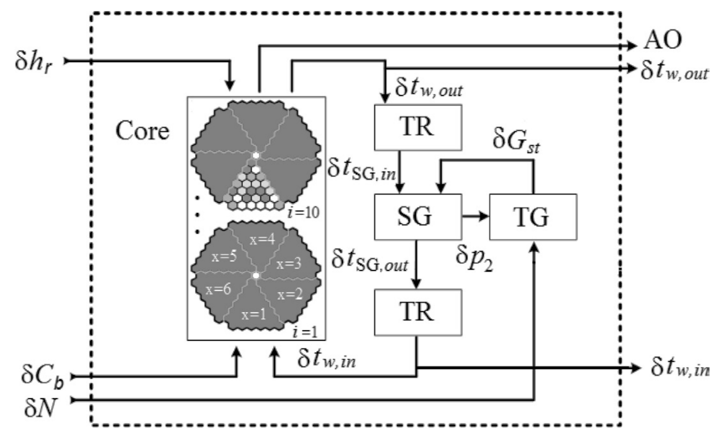

Fig. 2. The structure of the distributed model of the VVER-1000 core implemented in Simulink: SG is steam generator; TR is turbogenerator; TR is transportation lag element

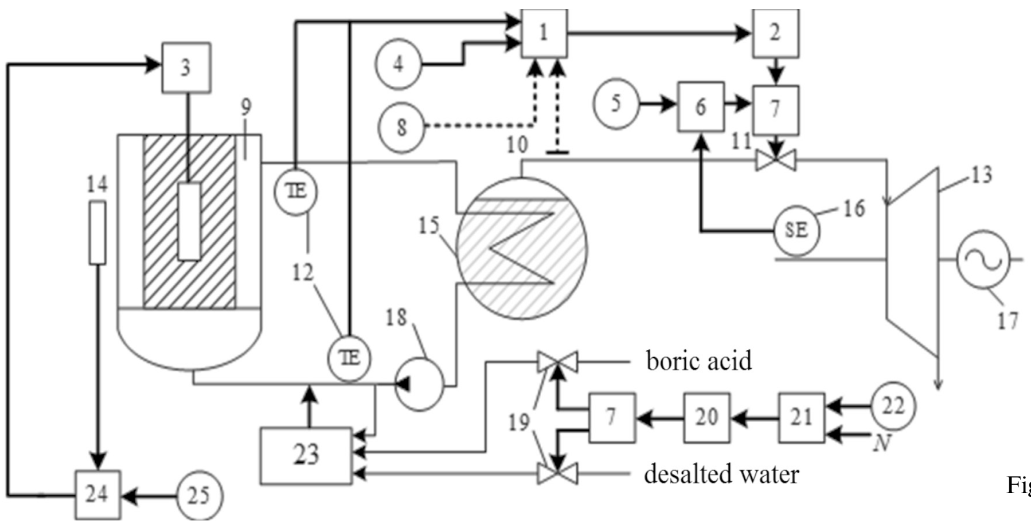

Fig. 3. The schematic diagram of improved reactor power CP

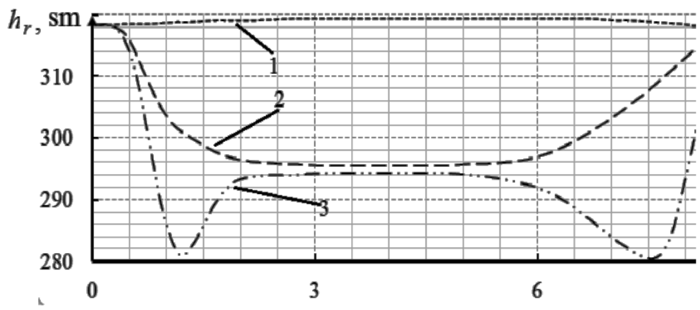

Fig. 4. The change of the regulating group position in VVER-1000 daily load-follow mode for program 1:
1, 2, 3 is improved, known and traditional ACS, respectively

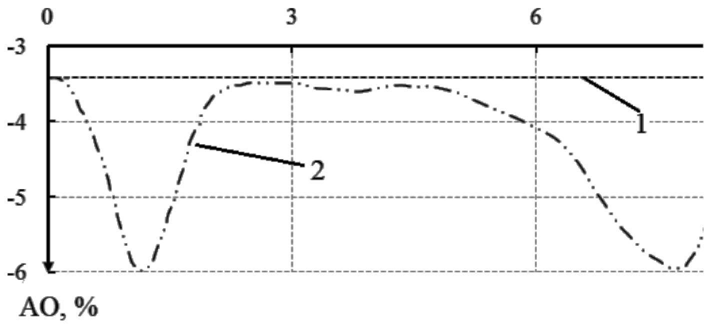

Fig. 5. The change of AO in VVER-1000 daily load-follow mode for program 1:
1, 2 is improved and traditional ACS, respectively

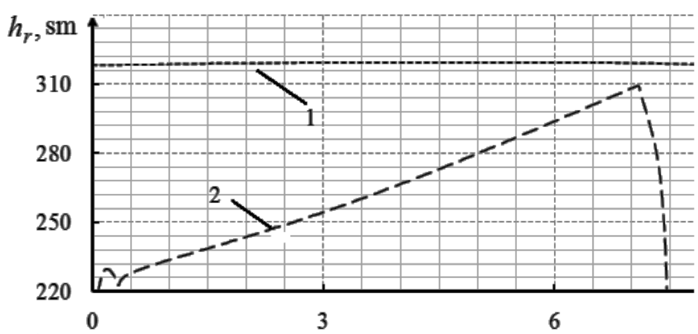

Fig. 6. The change of the regulating group position in VVER-1000 daily load-follow mode for program 2:
1, 2 is improved and traditional ACS, respectively

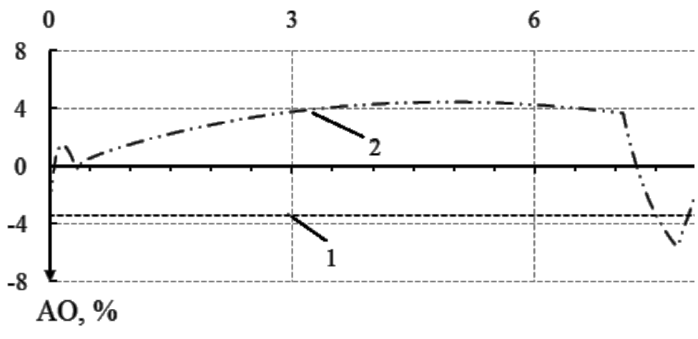

Fig. 7. The change of AO in VVER-1000 daily load-follow mode for program 2:
1, 2 is improved and traditional ACS, respectively

For program 1 ($<t>$ = const), the amplitude of changing the regulating group position in VVER-1000 load-follow mode according to the daily loading cycle 100 %→80 %→100 %, using: improved automated control system (improved ACS), known automated control system proposed in [6] (known ACS), and traditional automated control system (traditional ACS), is shown in Fig. 4.

It can be seen that, for the program keeping the core averaged coolant temperature constant, using the improved ACS in VVER-1000 daily low-follow mode has resulted in a considerably decreased amplitude of moving the control rods compared to both the known and traditional ACS.

For program 1 also, the amplitude of changing axial offset in VVER-1000 load-follow mode according to the daily loading cycle 100 %→80 %→100 %, using the improved and traditional ACS, is shown in Fig. 5.

Thus using the improved ACS in VVER-1000 daily load-follow mode for the program keeping the average coolant temperature constant, the change of AO is considerably lower compared to the traditional ACS.

For program 2 (p_2 = const), the amplitude of changing the regulating group position in VVER-1000 load-follow mode according to the daily loading cycle 100 %→80 %→100 %, using the improved and traditional ACS, is shown in Fig. 6.

It can be seen that, for the program keeping the second circuit inlet steam pressure constant, using the proposed ACS in VVER-1000 daily load-follow mode has resulted in a considerably decreased amplitude of moving the control rods compared to the traditional ACS.

At last, for program 2, the amplitude of changing axial offset in VVER-1000 load-follow mode according to the daily loading cycle 100 %→80 %→100 %, using the improved and traditional ACS, is shown in Fig. 7.

Hence, using the proposed ACS in VVER-1000 daily load-follow mode for the program keeping the second circuit inlet steam pressure constant, the change of AO is considerably lower compared to the traditional ACS also.

Data Mining and related processes. Data Mining is a process of detecting dependencies in data, which must be automatic or semiautomatic at least. Also, the processes which are related to DM are using different intelligent techniques of a statistical and mathematical analysis, which allow obtaining useful information and determining its dependencies on datasets in varying degrees. The overall goal of the data mining process is to extract information from a dataset and transform it into an understandable structure for further use. At the same time, certain dependencies must demonstrate a directional advantage in something, usually in the economic aspect [9]. Concerning this study, it is proposed to use knowledge discovery. Data mining is the analysis step of the “knowledge discovery” process. Knowledge discovery shows the process of automatically searching large volumes of data for patterns that can be regarded as knowledge about the data [10].

A decision support system (DSS) is a computer-based information system that supports business or organizational decision-making activities. DSSs serve the management, operations, and planning levels of an organization and help people make decisions about problems that may be rapidly changing and not easily specified in advance, i.e. unstructured and semi-structured decision problems.

Regression is a data mining (machine learning) technique used to fit an equation to a dataset. The simplest form of regression, linear regression, uses the formula of a straight line ($y = mx + b$) and determines the appropriate values for m and b to predict the value of y based upon a given value of x.

Material and Methods

The process of DM is not a trivial task and, consequently, the cross industry standard process for data mining (CRISP-DM) and design science research methodology (DSRM) were used to achieve the goals, which is a lightweight way for organizing, understanding, implementation and development of analysis [9, 11].

Design science research is a set of analytical techniques and perspectives for performing research in information systems. Design science research involves the design of novel or innovative artefacts and the analysis of the use and/or performance of such artefacts to improve and understand the behavior of aspects of information systems. In design science research, as opposed to explanatory science research, academic research objectives are of more pragmatic nature. Research in these disciplines can be seen as a quest for understanding and improving human performance

This is achieved by the CRISP-DM methodology, which allows dividing the intellectual analysis into 5 phases. Thus, the current study is based on the CRISP-DM methodology. CRISP-DM stands for cross-industry process for data mining. The CRISP-DM methodology provides a structured approach to planning a data mining project. It is a robust and well-proven methodology. We do not claim any ownership over it. We did not invent it. We are however evangelists of its powerful practicality, its flexibility and its usefulness when using analytics to solve thorny business issues. It is the golden thread that runs through almost every client engagement.

In this study, as an application of DM, the free software Waikato Environment for Knowledge Analysis (Weka) was used. Weka is a set of visualization tools and algorithms for DM solutions and forecasting problems in conjunction with a graphical user shell for an access to them. Linear Regression, REPTree and M5P algorithms were used in the practical part of DM. After analysis, each model shows such metrics as correlation coefficient (CC), mean absolute error (MAE), root mean squared error (RMSE), relative absolute error (RAE), root relative squared error (RRSE), total number of instances (TNI).

Datasets for intelligent analysis were prepared by experimental-mathematical modelling with NPP load-following from 100 % to 80 % and back in 8 hours by Simulink of the Matlab software package. The dataset has variables such as the axial offset (AO, %), the energy release of the reactor (Q, %), the position of the 10th regulating group of control rods (hSUZ, cm), the concentration of 135J (cJ, unit/cm^{-3}), the concentration of 135Xe (cXe, unit/cm^{-3}), the input temperature of the coolant in the reactor core (t_{in}, r.u.), the average temperature of the coolant in the primary circuit (t_{av}, r.u.), the output temperature of the coolant it the reactor core (t_{out}, r.u.), the steam pressure in the second circuit (P, r.u.), the steam flow in the second circuit (Gst, kg/sec), and the output electric power of generator (PG, %).

Study Description

Business Understanding. The first phase of the methodology is focused on the understanding of the research object, main goals and requirements from a business point of view. The purpose of this work is to provide useful and relevant information to operators of the reactor facilities, which will show the benefits of using a particular CP.

The business goal of this paper is to show the different advantages and characteristics of VVER-1000 in two CP for a load-follow mode using DM. In the near future, it will help to choose what CP is better to use at NPP. At the beginning, it is necessary to mention that forecasting the variables for a nuclear facility is a complicated procedure as the facility is non-linear and has a plenty of dependencies of various parameters. There is a mathematical multi-zone VVER-1000 model, which was previously developed and allows obtaining the necessary parameters for a specified period of operation of the reactor facility by the mathematical modelling method, but this kind of model cannot predict the behavior of any of the parameters in this object [9].

The datasets were obtained for performing this study by simulating a VVER-1000 nuclear power facility in load-follow mode using the Simulink of Matlab software package for this purpose. As the targets of DM, characteristics a nuclear facility such as the axial offset (AO, %), the height of the control rods in the reactor core (hSUZ, cm) and the output electric power of generator (PG, %) were used.

Data Understanding. The implementation of the DM models depends on datasets which were obtained by simulation. After the simulation of the facility in a load-follow mode with change of the output electric power of generator from 100 % to 80 % and

Table 1. Distribution of Variables for Tav CP

Tav CP	**MIN**	**MAX**	**MEAN**	**stDEV**	**Unique, %**
AO, %	-23.128	-3.415	-22.257	2.712	70
Q, %	83.942	99.984	84.573	2.084	17
hSUZ, cm	273.648	321.074	277.407	5.543	97
cJ, unit/cm^{-3}	4.07E+16	4.46E+16	4.23E+16	1.15E+15	100
cXe, unit/cm^{-3}	3.43E+16	3.48E+16	3.46E+16	1.32E+14	100
t_{in}, r.u.	-0.009	2.399	2.89	0.31	11
t_{av}, r.u.	-0.223	0.128	0	0.008	6
t_{out}, r.u.	-2.378	-0.002	-2.288	0.311	11
P, r.u.	0	0.403	0.386	0.052	10
Gst, kg/sec	-81.718	-0.33	-78.715	10.697	10
PG, %	80	99.91	80.707	2.62	10

Table 2. Distribution of Variables for TinB CP

TinB CP	**MIN**	**MAX**	**MEAN**	**stDEV**	**Unique, %**
AO, %	-3.413	-3.409	-3.411	0	3%
Q, %	87.223	100	90.375	3.015	99%
hSUZ, cm	318.091	319.307	318.49	0.448	67%
cJ, unit/cm^{-3}	4.18E+16	4.46E+16	4.36E+16	9.65E+14	100%
cXe, unit/cm^{-3}	3.42E+16	3.47E+16	3.44E+16	1.44E+14	100%
t_{in}, r.u.	-0.016	0.004	-0.001	0.003	20%
t_{av}, r.u.	-2.001	0	-1.508	0.471	98%
t_{out}, r.u.	-4.001	0	-3.014	0.942	99%
P, r.u.	-0.001	0.153	0.115	0.037	92%
Gst, kg/sec	-77.504	0.376	-58.347	18.322	99%
PG, %	81.004	100.031	85.708	4.504	99%

back in 8 hours, the samples of datasets were used. The sample dataset using a CP that implements the average temperature of the coolant in the reactor core (Tav) was composed of 10356 records.

The sample of dataset using the compromise-combined program (TinB) was composed of 9848 records. Each sample of dataset has been organized by simulation time, but it should be noted that the option such as the simulation time was excluded in both CP. This is due to the fact that this option does not bear any scientific value. For both CP, the following parameters were chosen: AO – the axial offset, %; Q – the energy release of the reactor core, %; hSUZ – the position of the 10th regulating group of control rods, cm; cJ – the concentration of ^{135}J, unit/cm^{-3}; cXe – the concentration of ^{135}Xe, unit/cm^{-3}; t_{in} – the input temperature of the coolant in the reactor core, r.u.; t_{av} – the average temperature of the coolant in the primary circuit, r.u.; t_{out} – the output temperature of the coolant it the reactor core, r.u.; P – the steam pressure in the second circuit, r.u.; Gst – the steam flow in the second circuit, kg/sec; PG – the output electric power of generator, %.

Tables 1 and 2 demonstrate the statistical analysis for each parameter.

Comparing each variable in both tables, we can say that AO has more unique data in Tav program than in case of TinB program. Also, standard deviation (stDEV) of AO is zero in case of TinB program. It can be explained that AO is controlled by automation control system in case of TinB. The second variable Q of both tables has a large difference as well. Q has more unique data in TinB program than in case of TinB program. The standard deviation (stDEV) of Q is almost the same in both CP. hSUZ of Tav program has more unique data compared to hSUZ of TinB program, where 97 % vs. 67 %. However, in case of stDEV, hSUZ of TinB program has lower value than hSUZ of Tav, where 0.448 % is instead of 5.543 %. It is said that TinB program very rarely uses the control by control rods. As for cJ and cXe, the CP have similar values and unique data is 100% in both cases. The sixth variable Tin of TinB program has the unique data 2 times higher than Tin of Tav program and the stDEV is 100 times lower. All other variables such as Tav, Tout, P, Gst and PG of TinB have unique data with value more than 90%, and in the case of Tav program these variables have the unique data with value less than 12%. It is said that TinB program has many changes in such variables for a load-follow mode in contrast to the Tav program. As for the stDEV, Tav, Tout, P, Gst and PG of TinB program have somewhat higher values than in case of Tav program.

Data Preparation. As previously mentioned, the current study suggests making a prediction of the important parameters of the VVER-1000 NPP with in load-follow mode. It is needed to use the regression techniques to be sure that the datasets to be used can apply the appropriate DM approaches. However, the initial data obtained by the simulation of the power unit in 8 hours of load-follow mode from 100% to 80% and back is not required for sorting the time data.

Also, it is necessary to mention that the data has 11 attributes (i.e. variables). There is no need to forecast all the attributes, because only 3 attributes of the data are most important, although it is not allowed to completely exclude others.

Concerning this study, parameters were studied such as axial offset (AO), which is a special integral parameter in a quantitative measure form of the steady energy release by height of the reactor core; the height of the control rods (hSUZ), which is one of the most important parameters in NPP because it has direct influence on changes in the processes taking place in the reactor core; the output electric power of generator (PG), as well as the above-mentioned parameters, is one of the most important as well, because it is very important to control, register and forecast for economic and business points of view.

From the above it follows that AO (%), hSUZ (cm) and PG (%) were used as forecasting targets.

Modelling. At this stage of the research, it is very important to choose the best methods of DM. To solve this problem, regression algorithms of DM such as Linear Regression (LR), REPTree and M5P were chosen. Selection of these algorithms is based on the following characteristics: actual (simulated) data values, availability and efficiency of use. The chosen algorithms completely correspond to the above-mentioned characteristics. It should be mentioned as an important aspect that the modeling stage is the implementation of testing mechanisms. The simulation was carried out by 10 Folds Cross Validation. Many references suggest using 10 Folds Cross Validation because of good results [12].

The developed models can be represented by the following expression:

$$M_n = \{A_a; CP_b; V_c; TDM_d; T_e; SM_f\}.$$

The model M_n belongs to an approach (A) regression and is composed by type of CP (CP), variables (V), DM technique (TDM) and type of target (T) and sampling method (SM):

$$A_a = \{Regression_1\}$$
$$CP_b = \{Tav_1, TinB_2\}$$
$$V_c = \{All_1, (AO,\ hSUZ,\ cJ,\ cXe,\ Tav,\ PG)_2,\ (AO,\ hSUZ)_3, (AO,\ cJ)_4, (AO,\ cXe)_5,\ (AO,\ Tav)_6, (AO,\ PG)_7, (hSUZ,\ cJ)_8,\ (hSUZ,\ cXe)_9, (hSUZ,\ Tav)_{10},\ (hSUZ,\ PG)_{11}, (cJ,\ PG)_{12}, (cXe,\ PG)_{13}, (Tav,\ PG)_{14}\}$$
$$TDM_d = \{LR_1, M5P_2, REPTree_3\}$$
$$T_e = \{AO_1, hSUZ_2, PG_3\}$$
$$SM_f = \{10 - Folds\ \ Cross\ \ Validation_1\}$$

Using this notation for representing DM models, it is possible to present a particular model implemented. For instance, the model (M_1) follows the regression approach using the data from Tav CP and all data variables, the technique LR with AO target and the sampling method 10-Folds Cross Validation and is expressed as follows:

$$M_1 = \{A_1; CP_1; V_1; TDM_1; T_1; SM_1\}$$

Accordingly, for each CP 42 models were obtained with one technique. In total, 252 models were obtained using the above expression.

Discussion

A large number of models were obtained during the experiment. The results were quite satisfactory. However, many models do not have a good value of the RRSE metric in both cases of CP. These results were dropped and then the best 8 models were totally obtained. The results of these 8 models are shown in Tables 3 and 4.

Table 3. The best results of Tav CP

Scenario	Variables	Target	Algorithm	CC	MAE	RMSE	RAE	RRSE	TNI
42	Tav, PG	PG	LR	0.017	1.2749	2.6204	99.9385	100.0094	10356
6	All	PG	M5P	1	0.0036	0.013	0.2789	0.4974	10356
12	AO, hSUZ, cJ, cXe, Tav, PG	PG	M5P	0.9999	0.0069	0.03	0.5387	1.1437	10356
42	Tav, PG	PG	M5P	0.7777	0.516	1.6509	40.4485	63.0077	10356

Table 4. The best results of TinB CP

Scenario	Variables	Target	Algorithm	CC	MAE	RMSE	RAE	RRSE	TNI
42	Tav, PG	PG	LR	0.9999	0.034	0.07	1.0761	1.5538	9848
6	All	PG	M5P	1	0.001	0.0029	0.0323	0.064	9848
12	AO, hSUZ, cJ, cXe, Tav, PG	PG	M5P	1	0.0059	0.0188	0.1867	0.4172	9848
42	Tav, PG	PG	M5P	0.9999	0.0271	0.0681	0.859	1.5124	9848

As already mentioned, the model results are compared only by PG target. Moreover, in some cases, some models show the value of the RRSE metric higher than 2%.

As we can see from Tables 3 and 4, the models of scenarios with numbers 6 and 12 show almost the same result in case of TinB. The models of 6, 12 scenarios and TinB CP have correlation coefficients equal to 1. The models of 6, 12 scenarios and Tav CP have correlation coefficients equal to 1 and 0.9999. However, these models of TinB program have several times lower values of RRSE than models of Tav program.

The models of scenarios with numbers 42 and Tav program, but with different algorithms, show worse results in comparison to TinB program since the models of Tav program have correlation coefficients equal to 0.017 and 0.7777 and the models of TinB program to 0.9999. Moreover, the models of Tav program have RRSE equal to 100.0094 and 63.0077 in case of Tav. At the same time, the models of TinB program have RRSE equal to 1.5538 and 1.5124, and it is much lower than in case of Tav program.

Conclusions

The above tables show the best results for the two CP of NPP. Based on the data of these tables, it can be concluded that DM using regression algorithms demonstrated almost each model that relates to the improved compromise-combined CP (TinB). It has better results than the models relating to the CP with the constant average temperature of the coolant in the reactor core (Tav). However, it should be mentioned that the results with AO and hSUZ targets were not included in Tables 5 and 6. In case of the improved compromise-combined CP, it can be explained by the fact that almost all results are higher than 10% of the RRSE metric. In addition, in case of the results relating to the CP with the constant average temperature of the coolant in the reactor core, the regression models showed good results, which on the average is less than 1% of the RRSE metric.

This study has shown that using DM techniques can explain relationships between parameters of VVER-1000 NPP for the two CP in load-follow mode. DM algorithms such as Linear Regression, REPTree and M5P were used. The Weka software was used to extract useful data. It allowed us to apply the above algorithms and to obtain sufficiently satisfactory results.

Moreover, it is safe to assume that the traditional idea of data, which are combined with 10 Folds Cross Validation and regression algorithms, demonstrates itself as the best tool to get useful data, accordingly, of knowledge, from the studied data source.

Thus, this research work proves that the use of DM can show which CP of VVER-1000 NPP based on parameters of NPP load-follow mode, using the previously modelled data, is better.

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